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The Visible Nulling Coronagraph

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TPF

A Nulling Interferometer Based Instrument for TPF using a Single Aperture Telescope in Visible Light

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•**Now at MIT Center for Space Research, Cambridge, MA 02139**

Inner Working Angle, Key to Exo-Earth Detection

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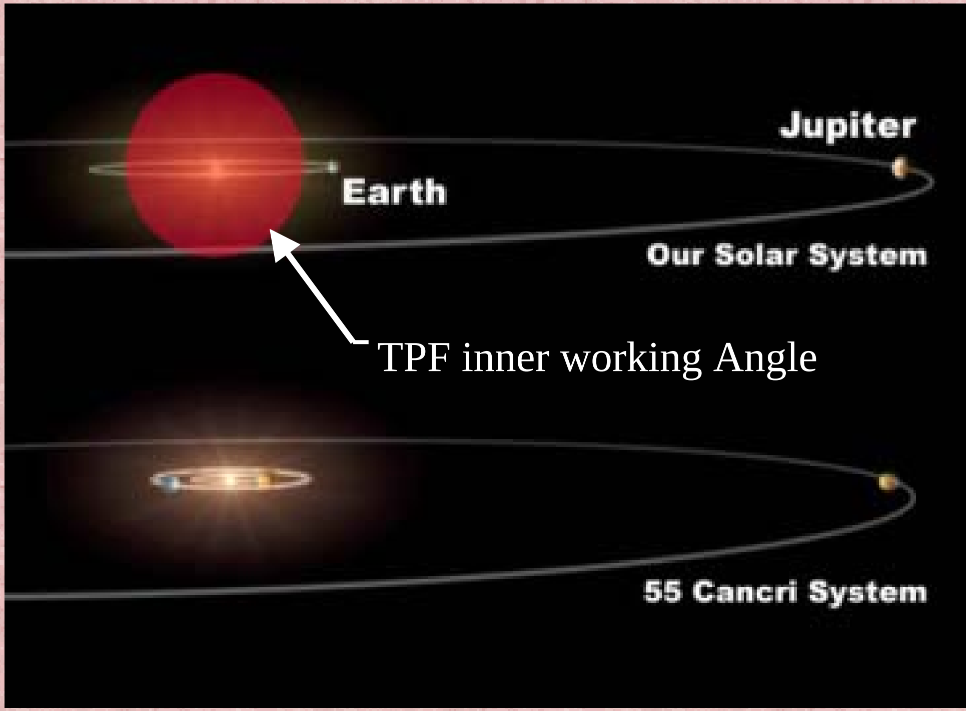
- The IWA, inner working angle is the angle inside which direct detection of a planet is not possible. (N*λ/D)
- Different types of coronagraphs have IWA with different values of N



- Typically the orbit of the planet is inclined wrt the line of sight and is not detectable over much of its orbit.
- If we want to be able to detect the planet over ~50% of its orbit, the IWA has to be < ~65% of the maximum star-planet separation.
- Even when the planet is detectable over 50% of its orbit, if we want to definitively say there is no planet (with 95% confidence) one has to look ~ 4 times.

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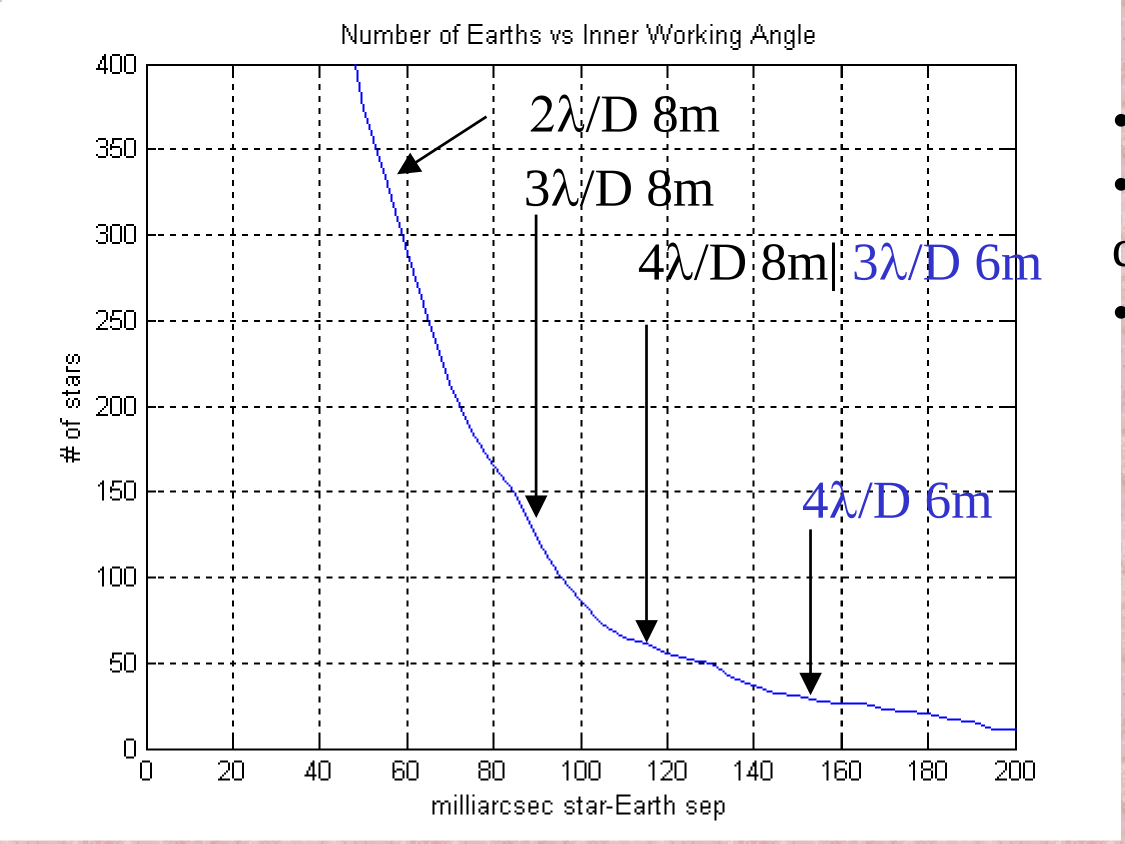
Discovery Potential vs IWA



- Search through Gliese Cat
- Late F,G,K, and M main seq dwarfs
- Habitable Zone @ 300K

- Often used scaling law for cost of a telescope is $D^{2.5}$
- going from 3 => 4 λ/D is a factor of 2 in cost
    - a cost measured in billions of dollars

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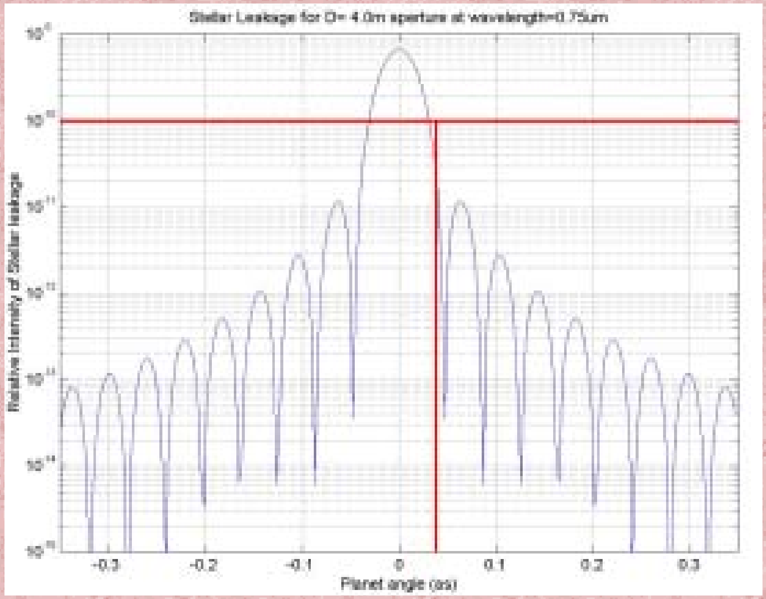
Why a Nuller for Visible TPF?

- **Small Inner working angle**
  - **Smaller primary mirror, √2 in diameter is a big deal**
  - **4~5m telescope is a candidate for a FULL TPF mission.**
- **Relaxed optical figure for telescope**
  - **λ/20 optics vs the requirements of 'ultra-precision' mirrors.**
- **Will ultimately prove much easier to achieve 10^{-10} suppression of starlight**
  - **Control of: Amplitude, Phase, Spectral width, Polarization, etc.**
- **Expandable to very large apertures using a segmented primary telescope.**
  - **Compatible with MEM's type deformable mirrors. (Same technology as used in million pixel computer projectors.)**



- **θ^4 interferometer leakage below 10^{-10} at θ~λ/D**

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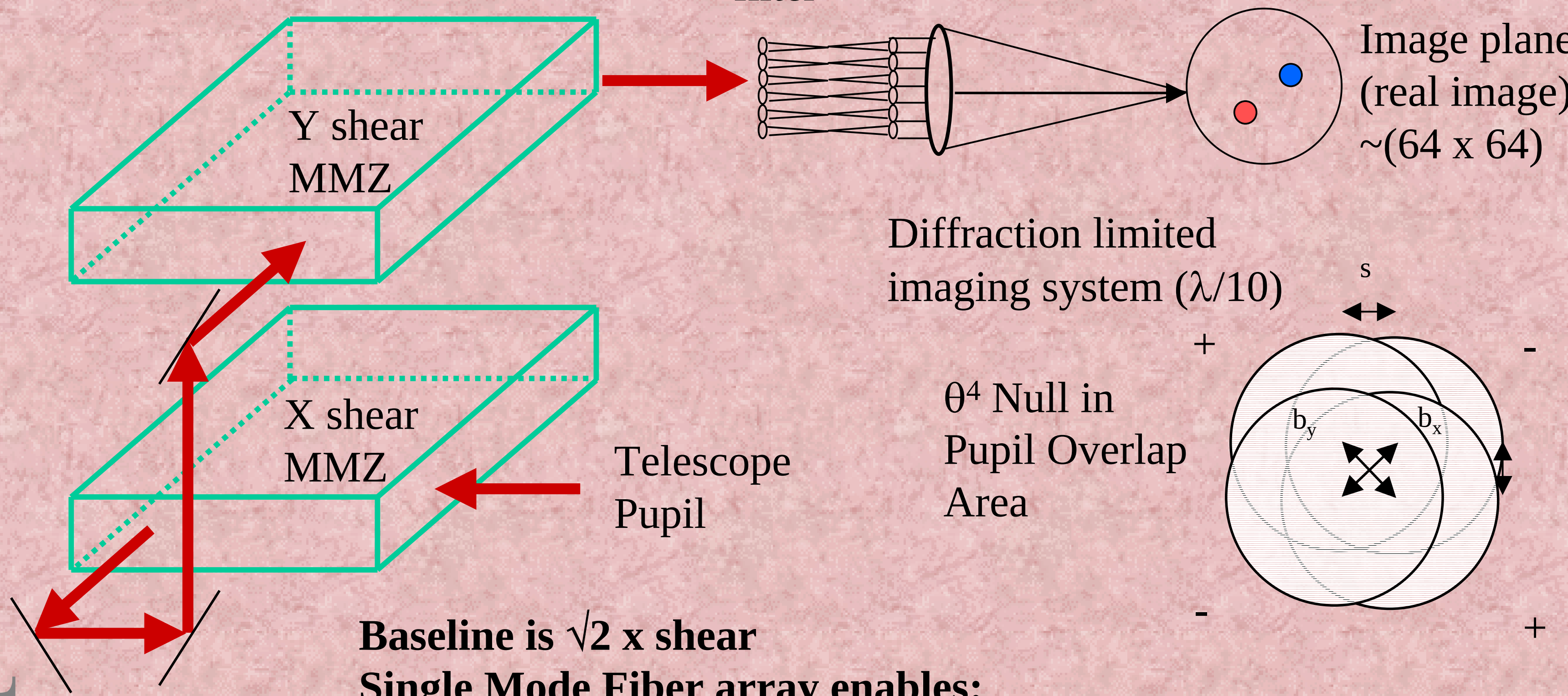
Visible Nulling System Concept



Baseline is √2 x shear

Single Mode Fiber array enables:

- **10^{-9} suppression achieved with 10^{-7} nuller and 100 lenslets**
- **10^{-10} suppression achieved with 10^{-7} nuller and 1000 lenslets**
- **Multiple sub-apertures make the detection less susceptible to Exo-Zodiacal Dust**
  - **Residual background is incoherent with planet image**
  - **Preserves field of view**

Visible Nulling System Concept (2)

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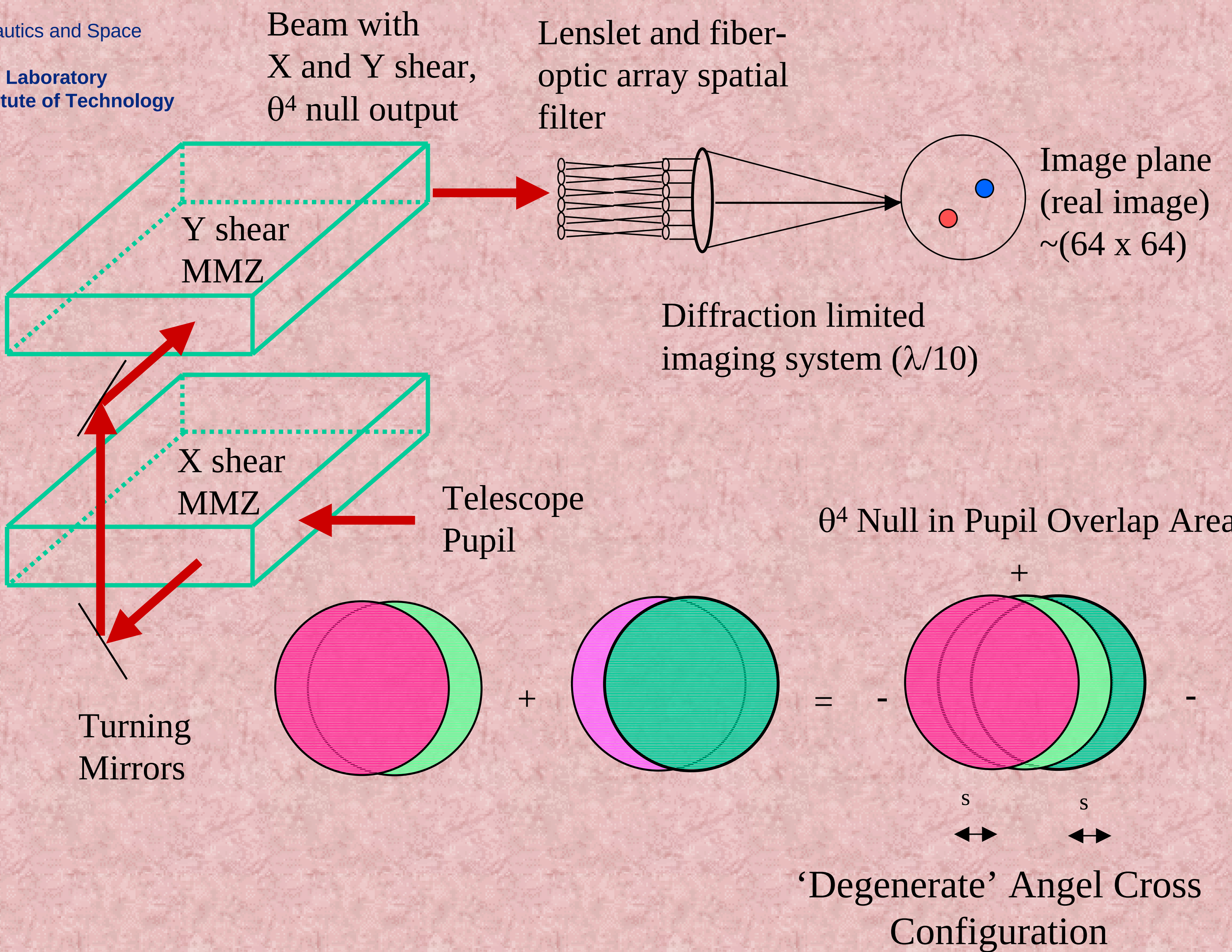

Achromatic Nulling Interferometer Demonstration (Shao & Serabyn)

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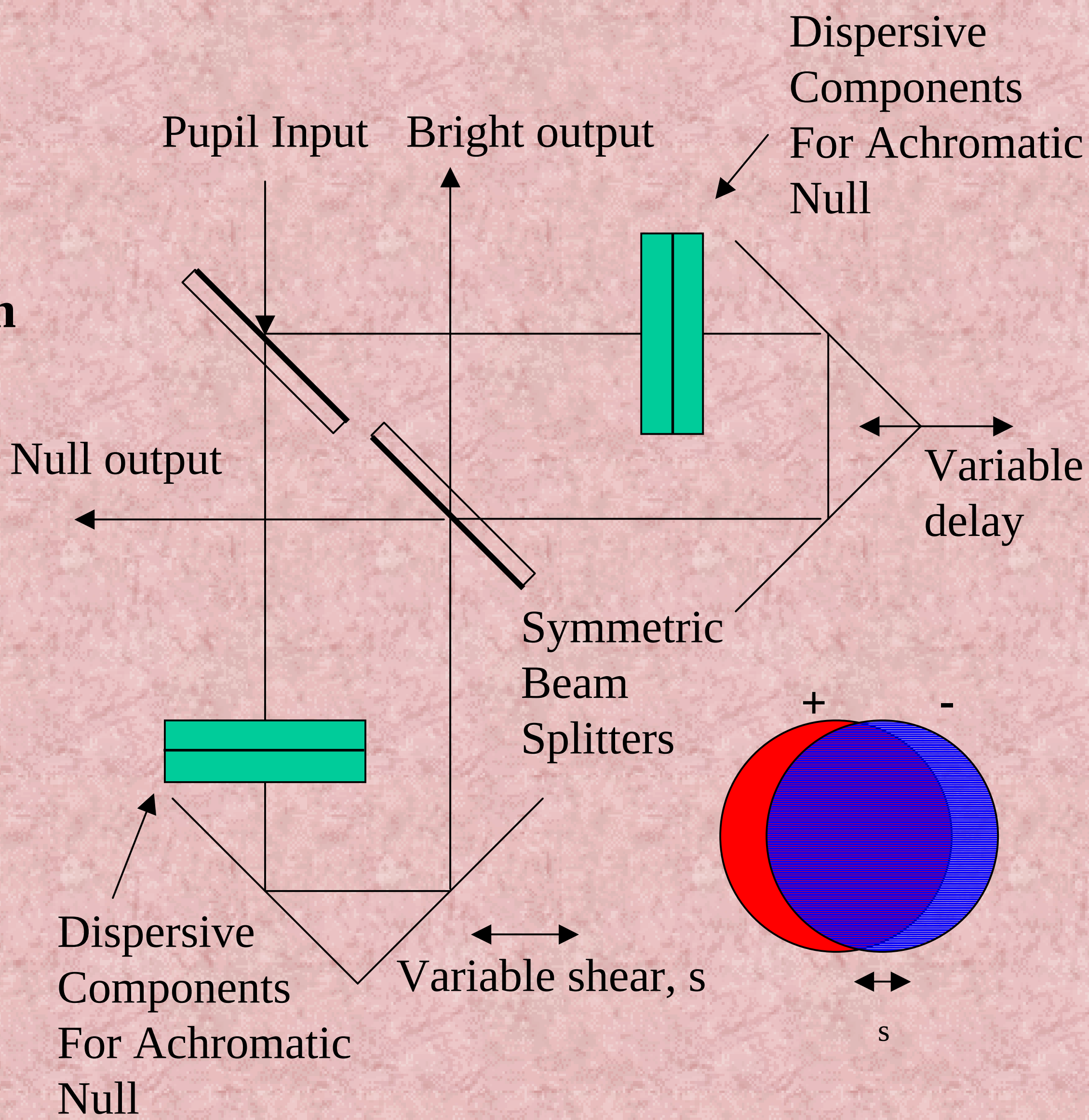
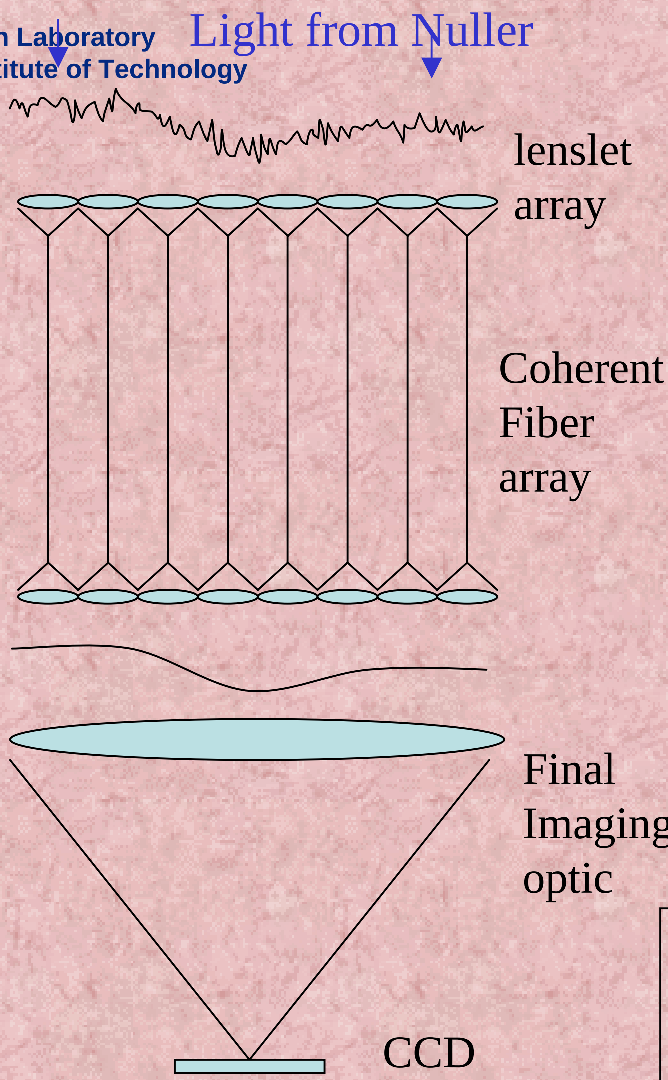
- **Single pupil input**
- **Symmetric design**
- **Preserves pupil orientation and polarization**
- **Pupil shear adjustable– variable null baseline**
- **Dielectric plates provide achromatic null**



Coherent Fiber Array Nulling Requirements



In a visible TPF based on a nulling interferometer

For Earth Detection:
Fiber array has ~ 1000 fibers

Final image plane has a field of view ~1000 airy spots (~30x30)

Average null of 1e-7 means that 1e-7 light spread over 1000 airy spots, or 1e-10 scattered light per airy spot.

Nulling requirement (Vis TPF/Earth) is
1e-7 for Q=1, planet flux = scattered light flux
3e-7 for Q=0.3

Requirement for Jupiter Imager ~10~100x easier

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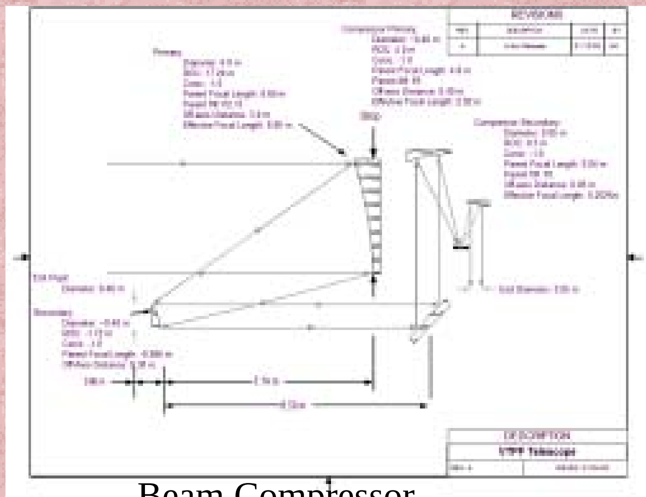
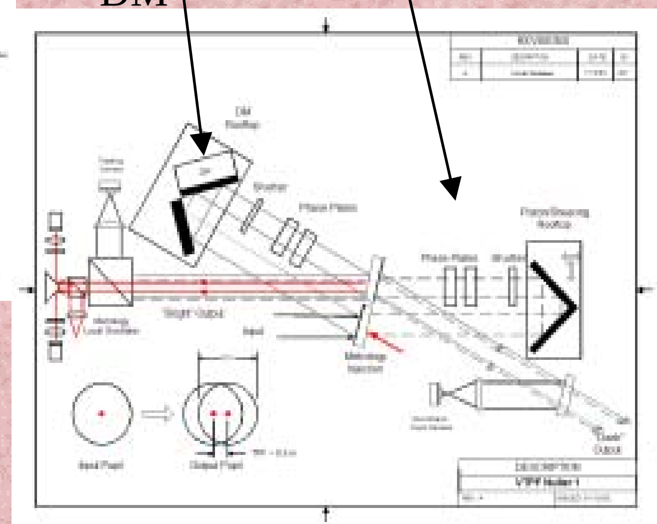
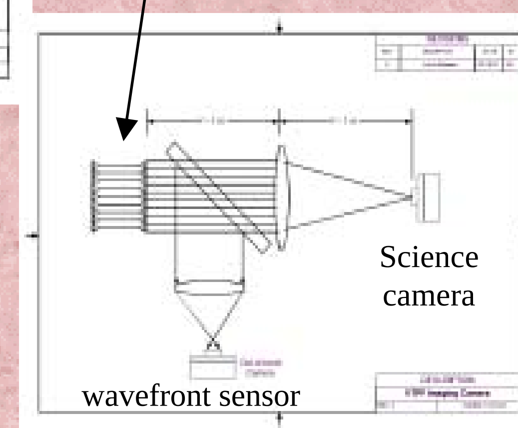
Functional Overview of Nulling Coronagraph







•Primary reimaged to DM's which are in turn reimaged to the input lenslet array. The output lenslet array is reimaged to the wavefront sensor CCD. (reimaging to eliminate xtalk between channels)

Nulling Technology Development

- Component Development Demonstration of Deep Nulling
- Single Mode Fiber Optic Array Fabrication
  - JPL
  - Penn State (U Florida)
- Deformable Mirror Demonstration
  - 361 channel MEMS DM (BU)
  - 1000 actuator goal
- System Demonstration
  - Multiple Aperture Nulls

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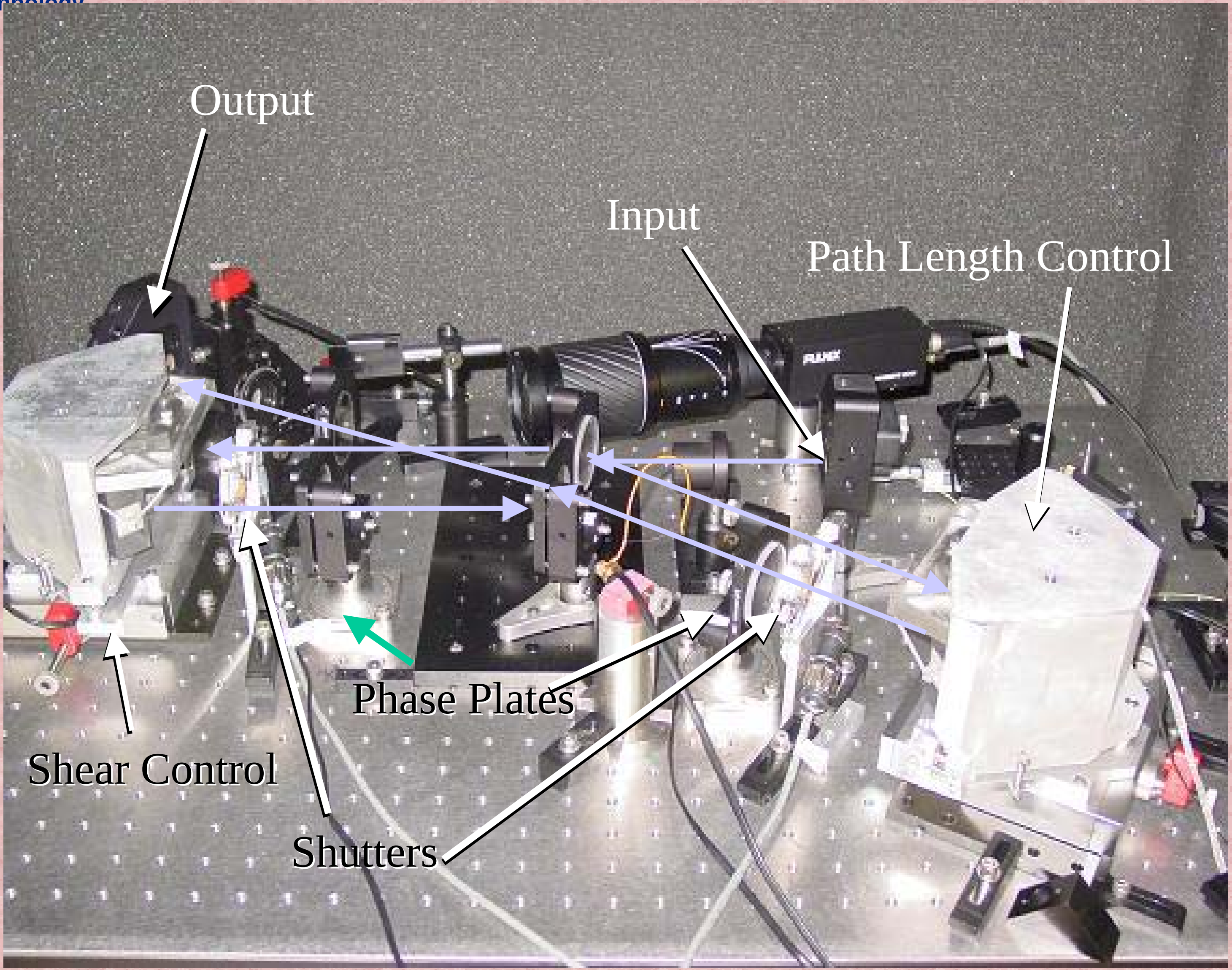
Nulling Interferometer Laboratory Set-up



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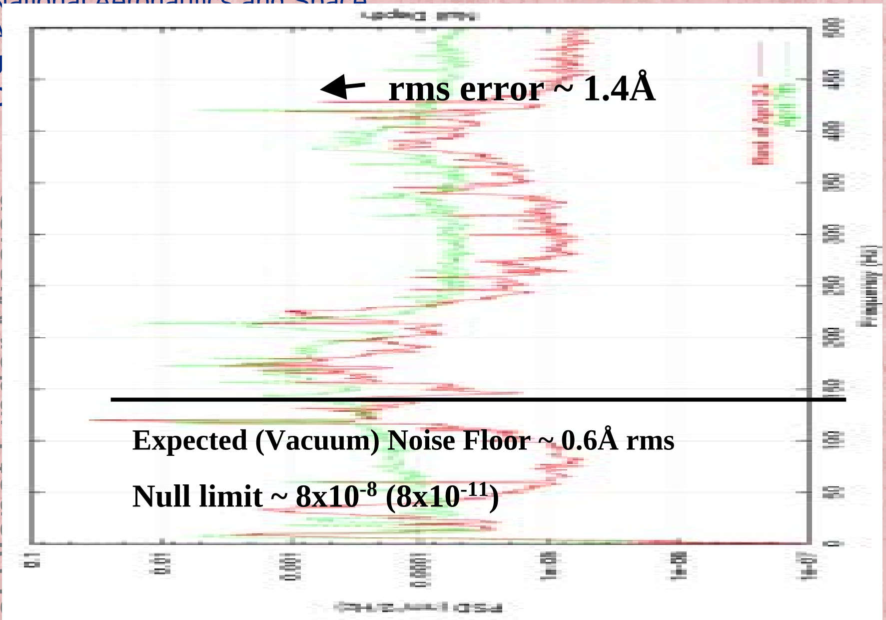
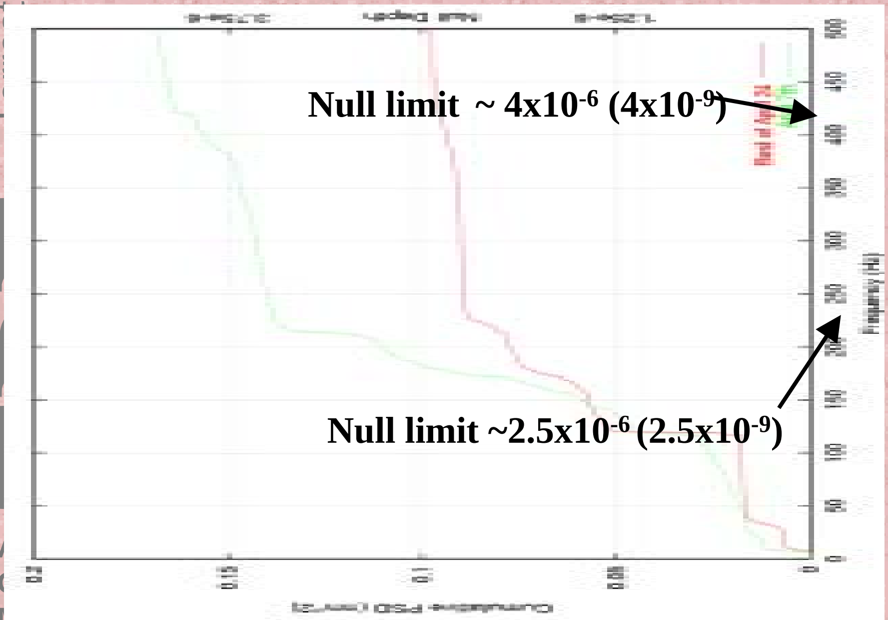
Deep Null Controlled by Laser Metrology

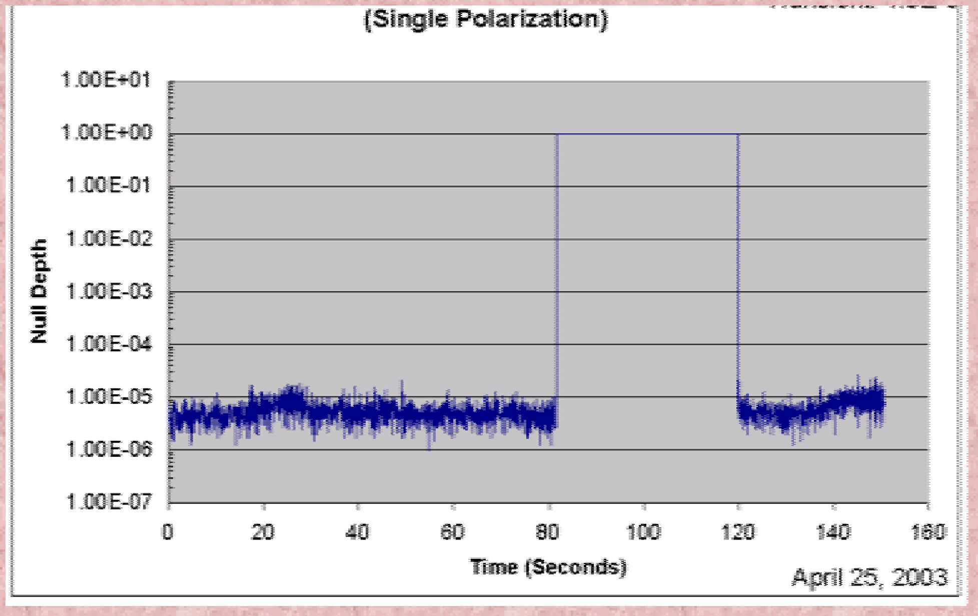


$$null\ depth \approx \frac{\sigma_\phi^2}{4}$$

λ = 635nm

- **Average null = $5.2x10^{-6}$ ($5.2x10^{-9}$ /airy spot)**
  - **50x from TPF goal**
  - **See SPIE 5170-21, Wallace et. al**





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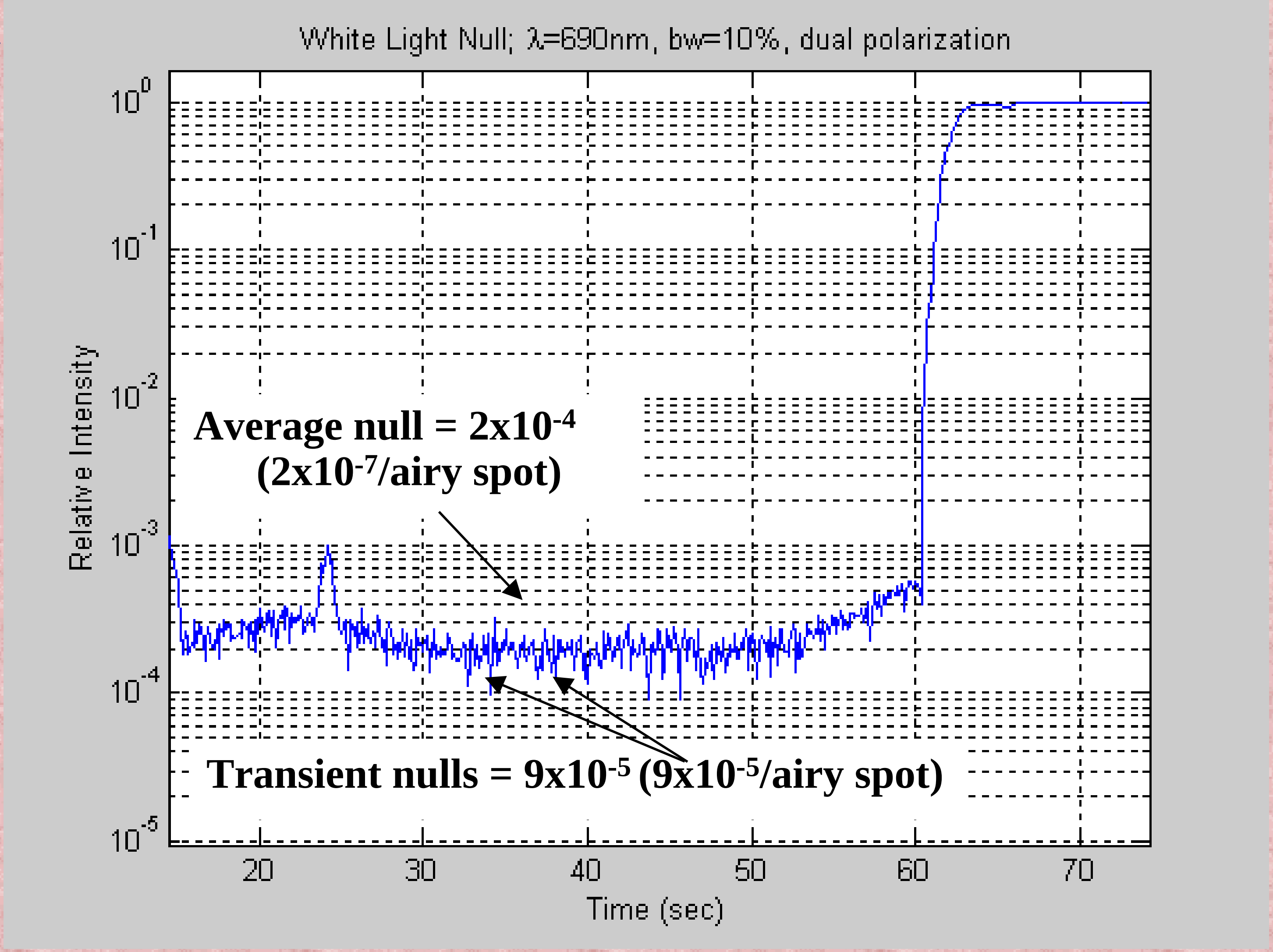
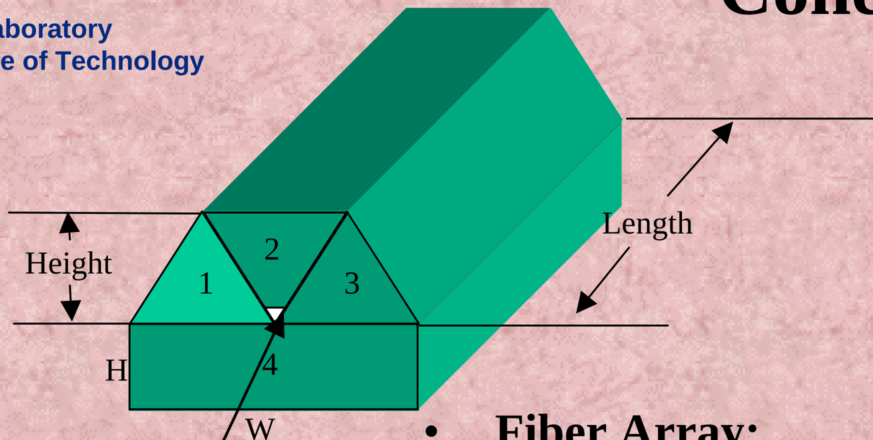
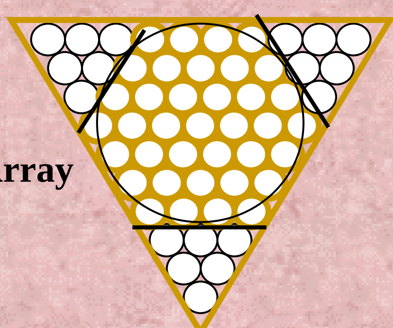
White Light Null Results



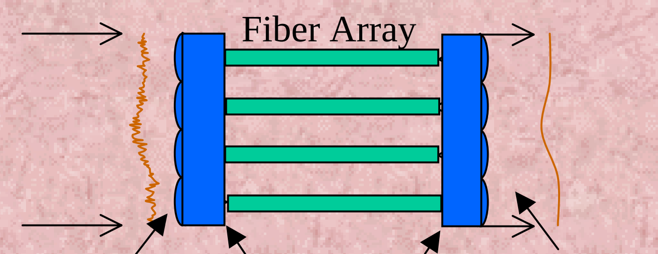
- Data = 10_21_03_08

Self Assembly of Fibers in (2nd Generation) Coherent Array



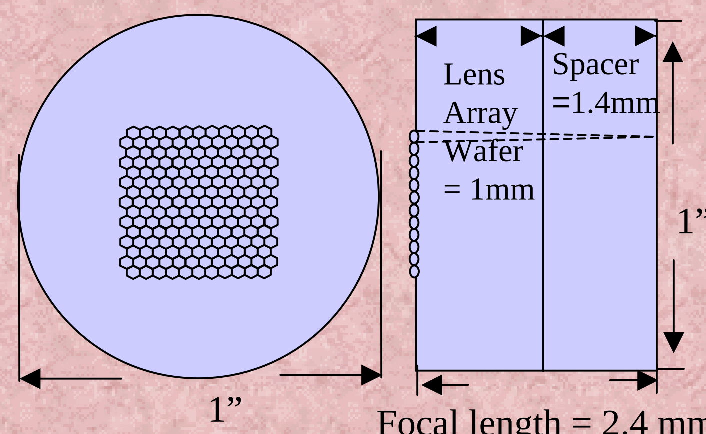


•**Fiber Array Detail**



- **Fiber Array:**
  - **3 Dove prisms on rectangular slab**
  - **Prism 2 corner is cut flat to accommodate Fibers**
  - **New Technology Report filed**

- **Lens Array**
  - **Monolithic Lens Array on thin substrate**
  - **Spacer bonded with thickness = focal length**
  - **Lens spacing 126.2μm**
  - **NA=0.048 @λ=0.632μm**



See SPIE 5170-22, Liu et. al. (2003); 5491-73, Ge (2004)

Fiber Array Regularity

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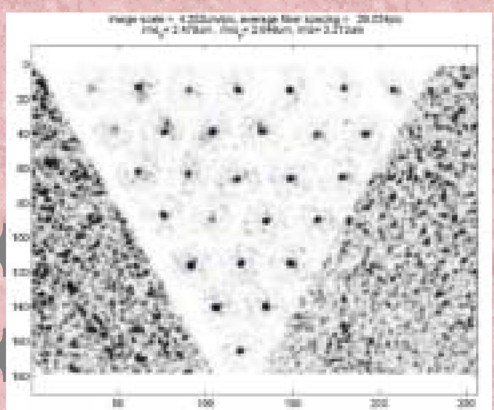
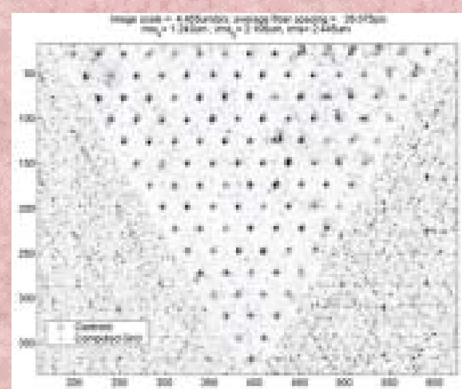
Photonic Crystal Fiber (PCF)



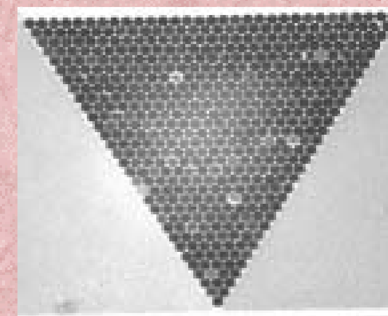
3.2μm rms over 28 fibers

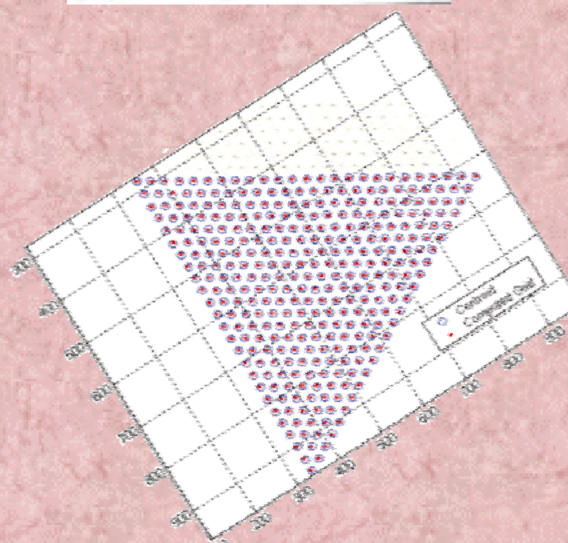
(Conventional) Single Mode Fiber



2.4μm rms over 120 fibers

Large Mode Field Single Mode Fiber





<3.9μm rms over 325 of 496 fibers (first 25 of 31 rows) (preliminary)

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Summary

- **Single Aperture Telescope with a Visible Nulling Coronagraph Capable of Imaging and Spectroscopy of Earth-line Planets (D~4m)**
  - **Resolution scales with shear (up to the diameter of telescope)**
- **Mission Concept and Instrument Defined**
- **Starlight Suppression is the Most Challenging Technology**
  - **Demonstrated Closed Loop Null @ 5.2×10^{-9}/airy spot using Laser Metrology**
    - **50x from TPF goal**
  - **Fiber Arrays under Evaluation**
    - **Conventional SM Fiber demonstrates fiber placement regularity**
      - **(pathfinder for future device)**
  - **BU DM Actuator Assessment**
    - **(Commercial) DM actuator structure is capable of small scale path length control (no technology development required)**
    - **Controllable actuator response for small displacements possible**
    - **Noise floor and error performance satisfies path length control requirements**
    - **Negligible cross-talk**

Future Work

- **Near Term**
  - **Deep White Light Nulls under Laser Metrology**
    - **$1x10^{-6}$goal (5-10% bandwidth)**
      - **10x from TPF goal**
  - **Single Mode Coherent Fiber Array Demonstration**
    - **Large Mode Field Diameter Fibers**
    - **361 Channel Array Goal**
- **Long Term Experiments:**
  - **Integration of Nuller and SMF Array in Test Bed System Demonstration on Test Bed**
  - **Multiple Channel Null Demonstration**
    - **Use of DM to control amplitude and phase**